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学位授与の要件	学位規則第４条第２項該当
学 位 論 文 名	Analysis of the Dynamic Response of a Controlled Detonation Chamber （制御爆破チャンバーの動的応答に関する解析）
論文審査委員	（主査） 教 授　南　二三吉 （副査） 教 授　小溝　裕一　　教 授　望月　正人　　准教授　田川　哲哉 Royal Military Academy 教授　Michel H. Lefebvre

論 文 内 容 の 要 旨

1. Need for this Work: Whereas the vessel response to static pressure is well known, the impulsive loaded (detonation) vessels remain a domain in which knowledge is still increasing. Design rules for statically loaded vessels exist since a long time, while design rules for dynamically loaded vessels have only recently been developed. There are still some parameters which remained uninvestigated, mainly related to the explosive charge and its influence on the vessel response. Study of how the vessel material changes due to dynamically induced pre-strain was also unknown.

2. Thesis Objectives: To assess the influence of the explosive charge on the vessel response and to assess the influence of dynamic pre-strain on material parameters such as tensile properties and fracture toughness.

3. Meeting the Thesis Objectives: The influence of several parameters of the explosive charge on the vessel response has been determined, clearly indicating which influences were important (nature of explosive, shape of charge, position of the charge) or less important (for example location of initiation). Fracture toughness is not influenced by dynamic pre-strain for temperatures above BDTT. Tensile properties on the contrary are significantly modified, with an increase in yield stress and a decrease in ductility.

4. Initial Collaboration with Japan: One application of detonation vessel is for the destruction of old chemical munitions, found in the sea (Japan) or in farmers' fields (Belgium). This technology has been in use in Japan for years now, with the help of Belgian experts in EOD and explosives for the development of the donor charge. The use of a closed detonation chamber of Japanese fabrication for the destruction of the Belgian legacy of old chemical munitions has led to an even closer collaboration between Belgium and Japan.

5. Influence of the Explosive Charge on the Vessel Response: These influences must be taken into account by designers and operators of detonation vessels, because they can significantly change the vessel response.

A. Nature of the Explosive: The nature of the explosive is the first key property of the explosive charge. A TNT-equivalent based on impulse is useful to estimate the effect of an explosive different than the one the design has been made for. If an explosive is unknown, relatively easy tests can be executed to determine the TNT-equivalent, as demonstrated in the thesis.

B. Shape of the Explosive Charge: A second key property is the charge shape. This shape determines the vessel response in a very significant way. Up to double values of peak strains can be reached by changing the spherical shape into a specific cylindrical shape. This indicates the importance of the charge shape. When non-spherical charges are used, great care must be taken when estimating/determining the effects of that charges.

C. Position of the Explosive Charge: The explosive charge (certainly when it is cylindrical) has an effect on a limited zone of the vessel. By moving the charge in the vessel, the vessel wall can be more uniformly damage (what increases its lifetime)

D. Initiation of the Explosive Charge: The initiation location of the explosive charge has virtually no influence on the vessel response. This means that the most practical location for the initiation can be selected without having an influence on the vessel response.

E. Splitting of the Explosive Charge: The use of two halve charges separated by a certain distance is, from a strain response point of view, very favorable. Peak strains are much lower at the vessel beltline. This practice can extent the vessel fatigue lifetime in a significant way.

F. Experimental Demonstration of Shakedown: With the cylindrical charges of 3 kg, large plastic strains have been induced in the vessel walls. Four of these shots have allowed to demonstrate a decreasing residual (= plastic) strain after each successive shot. Shakedown had not been completed after four shots however, and cracks in the vessel might have affected the vessel integrity in such a way that shakedown has been interrupted.

G. Potential benefit of a multi-layered vessel wall: The potential benefit of the multi-layer technology on the vessel response has not been proved by the experiments. However, multi-layer technology always offers the advantage of crack arresting between two layers.

6. Material Changes Because of the Dynamic Pre-strain: The dynamic pre-strain induced by the impulsive loading in different types of test specimens has allowed to determine its effect on different material properties.

A. Fracture Toughness: Charpy impact tests on loaded and virgin test pieces have shown that the fracture toughness and the ductility of the fracture are not influenced by the dynamic pre-strain for temperatures above the brittle-to-ductile transition temperature.

B. Tensile Properties: The dynamic pre-strain has a large influence on the tensile properties: the yield stress is considerably increased, and the uniform elongation is significantly reduced.

7. CONCLUSIONS

A. Expected Results of the Research: The conclusions drawn from this work allow both vessel designers and operators to have a better knowledge of the potential influence of the properties of the explosive charge on the vessel response, and take these factors into account during vessel design or operations. This topic has too often been neglected when assessing the effect of an explosive charge, but it could be added to design codes to sensitize the detonation vessel designers and operators.

B. Some Important Recommendations based on the Research: For both detonation vessel designers and operators, some important recommendations can be made based on the conclusion of the thesis.

1. **Know the explosive.** Take the nature of the used explosive into account. Determine (or find in

references) the TNT-equivalent based on impulse for the explosive, and use this explosive instead of TNT for estimations or calculations.

2. **Consider the shape of the explosive charge.** This shape can have serious consequences on the vessel response, and must therefore not be neglected. Giving only a mass of explosive is not sufficient, the shape must be known as well.
3. **Use a cylindrical vessel.** Spherical vessel response is more difficult to predict in changing charge configurations, whereas cylindrical vessels offer the opportunity to place charges in different positions or split charges; two solutions which can extent the vessel lifetime significantly.
4. **Use a multi-layered vessel well.** The benefit for strain response has not been proved, but this type of wall will stop potential cracks from growing through the entire wall thickness.
5. **Allow initial plasticity in the vessel wall.** After shakedown, strains will be elastic without having passed the limits of accumulated plastic strain.
6. **Split charges whenever operationally possible.** This helps reduce peak strains and fatigue damage, without having an effect on the throughput of a vessel.
7. **Use the most practical/easy location of initiation**. Experiments have shown that the influence of the initiation location is inexistent.

論文審査の結果の要旨

第二次世界大戦時の化学兵器不発弾が今もなおベルギー，オランダ，フランス北部，独北西部などの土中に散在している。それらが発見された場合，安全な処理が必要なのは言うまでもなく，密閉チャンバー内で爆破処理する方法が一般的に採用されている。その際，チャンバーは衝撃爆破荷重を受けるので，爆破処理には高い安全性が要求されるが，衝撃爆破時のチャンバーの動的応答はほとんど解明されていなく，現状では専ら経験的な手法が用いられている。本論文は，チャンバーの安全制御の思想の下，衝撃爆破によるチャンバーの圧力変動や動的ひずみ応答に及ぼす諸因子の影響を明らかにし，安全・合理的なチャンバー設計の構築に資することを目的としている。本論文で得られた主たる結論をまとめると以下のようである。

(1) 衝撃爆破時のチャンバーの動的応答に影響を与える主要因子は，①火薬のアスペクト比（単軸と長軸の長さ比），②火薬の爆破パターン，③チャンバー内の火薬配列の３つである。同じ爆破処理効果を保ちながらチャンバーへの衝撃度を少なくするには，火薬形状を球状にすること，火薬の複数回爆破（火薬を１度に発火させるのでなく，火薬を分割して２回に分けて発火させるなど），火薬の分散配置（爆破位置の集中を避ける）が有効である。

(2) 火薬のアスペクト比の影響を定量的に調べるには，標準的に用いられる TNT 火薬よりも，種々の形状に成形しやすいエマルジョン火薬の方が適している。爆破時のピーク圧力ではエマルジョン火薬は同重量の TNT 火薬と等価，衝撃度ではエマルジョン火薬１ｋｇは TNT 火薬 0.7kg と等価であることを明らかにした。

(3) 火薬重量が小さいと爆破時にチャンバーは弾性挙動を示すが，火薬重量が大きいと塑性的な応答を示す。この時，チャンバーの塑性ひずみは火薬量に応じて大きくなるが，ある火薬量を超えるとシェークダウンし，ひずみ増分は減少傾向を示す。

(4) 衝撃爆破時の火薬形状などの基本パラメータの影響は，チャンバー内でなくとも戸外での爆破シミュレーションによって簡便に評価することができる。

(5) 火薬重量が大きいと，爆破処理時にチャンバーは動的な予歪をうける。多数回爆破処理されるときには，動的予歪の影響はその累積ひずみによって評価できる。チャンバー材料の強度は，予歪による加工硬化によって大きくなるが，延性は予歪量の分だけ低下する。一方，破壊靭性は，延性-脆性遷移温度よりも高温側ではほとんど影響を受けない。これらの知見は爆破処理分野では世界初のものである。したがって，チャンバーの安全制御のためには，延性-脆性遷移温度よりも高い温度で爆破処理を行いつつ，作用した予歪量の分だけ延性が低下することを設計条件に組み入れることが重要である。

以上のように，本論文は従来経験的にしか知られていなかった衝撃爆破パラメータの影響を定量的に明らかにし，爆破処理効果を保持しながらチャンバーへの動的損傷を最小にするオペレーション手順を提示するとともに，繰返し爆破処理による動的予歪の影響を世界で初めて明らかにした。得られた成果は，爆破チャンバーの安全制御設計分野極めて有意義であり，構造材料の衝撃応答評価分野，ならびに，動的強度設計工学の発展に資するところが大である。よって本論文は博士論文として価値あるものと認める。